



ontario hydro research division

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MARKHAM MTS #2 - GROUNDING SYSTEM STUDIES

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Tests were conducted at Markham MTS #2 and at the nearby 230-kV line/cable junction under simulated fault conditions in order to evaluate the adequacy of the grounding system performance. Measurements indicated that the ground potential rises and the touch and step voltages for an ultimate HV station fault current of 32 kA are kept below the allowable limits by interconnecting the ground grids at the station and at the line/cable junction. Simplified models were developed to generalize the results.

1.0 INTRODUCTION

Markham MTS #2 is a new customer-owned 230-kV transformer station located at the corner of HWY 48 and 14th Avenue in the Town of Markham. Two new 230-kV overhead lines tapped from the existing circuits C4R and C11R between Cherrywood TS and Richview TS are connected to underground Low Pressure Oil Filled (LPOF) cables about 260 m long to supply the two transformers at Markham MTS #2 (hereafter called station). The cable shields are bonded to the ground grid at the line/cable junction (hereafter called junction) and are connected to the station grid through ring gaps. Two 253 mm² (500 kcmil) insulated copper ground conductors, running along the cable circuits, interconnect the two ground grids. The skywires of the 230-kV circuits are terminated on the line structure at the junction and are connected to the junction grid. The two transformers at the station are rated 50/67/83 MVA, 230/28 kV, Y_g/Z_{cg} , where Z_{cg} means zig-zag connected with reactor grounding (1.5 Ω). The station supplies loads through eight 28-kV distribution feeders installed underground to HWY 48 and then carried on poles. The shields of the feeder cables are bonded to the ground grid at the station and to the distribution neutrals at the poles. Also four 127 mm² (250 kcmil) copper bonding conductors installed underground inside the station interconnect the station ground grid and the distribution neutrals at the poles. Verification of the grounding system design values was required especially in view of the extensive grounding network of overhead and underground conductors. Therefore, measurements were performed at the station and at the junction under simulated fault conditions in order to confirm the adequacy of the grounding system performance at both locations. The project was requested and funded by Design and Development Division - Transmission. The tests were conducted on May 29, 30 and 31, 1989.

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2.0 TEST PROCEDURE

Figure 1 shows the layout of the station and junction with respect to the grounding tests performed. The 230-kV circuit C4R between Cherrywood TS and Richview TS was taken out of service for test current injection and line grounding switches were closed at Cherrywood TS (remote ground) to sink the test current. A test current of approximately 25 A at 230 V, 67 Hz from a diesel generator installed in a Research Division van was injected between the station ground and the blue phase of the test circuit as shown in Figure 2. A temporary working ground was installed at Markham MTS #2 to connect the blue phase of the test circuit to the current source. All three phases of the test circuit were paralleled at the junction to reduce line reactance beyond this point and to reduce induction from the adjacent 230-kV circuit.

Measurements were performed under the different test conditions listed in Table 1.

TABLE 1
TEST CONDITIONS

<u>Test Condition</u>	<u>Current Injection Between Station Ground and</u>	<u>Both Insulated Bonding Conductors</u>	<u>Ring Gap on Test Circuit Cable Shield</u>
1	Remote Ground	Isolated	Closed
2	Remote Ground	Isolated	Opened
3	Junction Ground	Isolated	Opened
4	Junction Ground	Isolated	Closed
5	Junction Ground	Connected	Closed
6	Remote Ground	Connected	Closed
7	Remote Ground	Connected	Opened

Temporary working grounds were used at the junction to locally sink the test current for conditions 3, 4 and 5. Temporary working grounds were used at the station for connecting the insulated bonding conductors and closing the ring gap on the cable shield of the test circuit phase to ground. The ring gaps on the other two phases of the test circuit and on the adjacent circuit were not disturbed during the tests.

The following measurements were made:

- (a) The potential between a remotely grounded telephone pair at the station and local station ground.
- (b) A potential profile west of the station.
- (c) A potential profile west of the junction.
- (d) Current splits on the skywires, insulated grounding conductors, cable shields and distribution neutrals, where applicable.
- (e) Potentials between the isolated 253 mm² (500 kcmil) grounding conductors and the station ground.

- (f) Potentials between the isolated cable shields of the test circuit and the station ground.
- (g) Touch and step potentials at the station and at the junction.

In view of redundancy and time constraints only selected measurements were performed under each test condition. The potentials and current splits (both magnitude and phase angle) were recorded and scaled with respect to 1.00/Q A injected current using an HP3582A spectrum analyzer in conjunction with a differential amplifier. The analyzer is capable of discriminating 67 Hz test signals from 60 Hz noise. The currents were measured using clip-on current transformers with shunts.

Soil resistivity surveys using the Wenner method /1/ were conducted at the north-west corners of the station and the junction as shown in Figure 1. A Megger DET-2 ground resistance tester was used to take the Wenner readings.

Safety precautions were observed during the tests in order to control and minimize any hazardous voltages that might appear in the event of a system fault.

3.0 MEASURED RESULTS

3.1 Measured Soil Resistivity

Two soil resistivity surveys using the Wenner method /1/ were conducted on the open field near the site (see Figure 1 for survey locations). The weather on the test date was sunny and warm and the soil was moist due to previous rain. The apparent soil resistivities calculated from the measured Wenner data (equation 7.1 of the Grounding Guide /1/) are given in Table 2.

TABLE 2

MARKHAM MTS #2 - MEASURED APPARENT SOIL RESISTIVITIES

<u>Probe Spacing (m)</u>	<u>Measured Apparent Soil Resistivities (Q.m)</u>	
	<u>Survey #1</u>	<u>Survey #2</u>
1	87.6	24.1
2	116.7	49.8
5	102.4	74.5
10	115.7	105.5
20	115.0	125.0
50	117.5	137.0
100	83.6	103.7

3.2 Measured Ground Potential Rise

The measured ground potential rises (GPR) at the station and at the junction are given in Tables 3 and 4 along with modelled values. For potential profile measurements, the current leads to the junction and the potential lead were oriented at approximately right angles and therefore any mutual

couplings between them were neglected. The actual measured profile readings were plotted against inverse distance and extrapolated to infinite distance at the ordinate to give ground potential rise /5/. This method reasonably assumes uniform soil resistivity and point current injection. The Bell Telephone cable routed north of the station along the east side of HWY 48 parallels the distribution neutrals. Therefore, the ground potential rises measured on the Bell cable were corrected for induction due to neutral currents and the corrected results are presented in the tables. The "measured" ground potential rises presented in Table 4 were derived from the measured results for current injections between the junction and station grounds and between the station and remote grounds. The corresponding ground potential rises for an ultimate HV ground fault current of 32 kA are also given in Tables 3 and 4 in brackets.

3.3 Measured Current Splits

The measured current splits for 1.00/0 A test current injection are given in Tables 5 and 6 along with modelled results. The "measured" current splits in the station and junction grounds were calculated by subtracting the other measured splits from the total injected current.

3.4 Measured Exposure

Voltages measured between the station ground and the isolated grounding conductors installed between the station and the junction are given in Table 7 along with modelled values. The conductors were bonded to the junction grid and opened at the station. Note that this exposure is the sum of the induced voltage and the difference between the ground potential rises at the station and at the junction.

3.5 Measured Touch and Step Voltages

Limited measurements of mesh, fence touch and step voltages were performed at the station and at the junction due to time constraints. The maximum measured results are given in Tables 8, 9 and 10, along with modelled values. Voltages of approximately 15.0/20 mV/A and 45.3/32 mV/A were measured between the fence and ground grid at the station and at the junction respectively, with the two ground grids bonded through both the cable shield and the bonding wires and test current injected between the station and remote grounds.

TABLE 3

MARKHAM MTS #2 - GROUND POTENTIAL RISES
(With Current Injection Between Station Ground and Remote Ground)

Grounding Connection Between TS & JCT		² GPR at Station (mV/A)		² GPR at Junction (mV/A)	
Bonding Wires	Ring Gap on Cable Shield	¹ Measured	Modelled	¹ Measured	Modelled
Isolated	Closed	a) 91.0/ <u>15</u> b) 92.7/ <u>23</u> (2.97 kV)	76.1/ <u>16</u> (2.44 kV)	a) 163.5/ <u>38</u> (5.23 kV)	131.0/ <u>39</u> (4.19 kV)
Isolated	Opened	a) 194.0/ <u>41</u> b) 192.3/ <u>48</u> (6.15 kV)	196.7/ <u>44</u> (6.29 kV)	a) 190.0/ <u>34</u> (6.08 kV)	239.4/ <u>40</u> (7.66 kV)
Connected	Closed	a) 94.0/ <u>19</u> b) 96.0/ <u>26</u> (3.07 kV)	75.1/ <u>20</u> (2.40 kV)	a) 136.8/ <u>36</u> (4.38 kV)	126.2/ <u>37</u> (4.04 kV)
Connected	Opened	a) - b) 83.8/ <u>25</u> (2.68 kV)	79.0/ <u>24</u> (2.53 kV)	-	107.9/ <u>29</u> (3.45 kV)

1. Measured GPR: a) from profile, b) from telephone pair.
2. In brackets: GPR for an ultimate HV ground fault current of 32 kA.

TABLE 4

MARKHAM MTS #2 - GROUND POTENTIAL RISES
(With Current Injection Between Junction Ground and Remote Ground)

Grounding Connection Between TS & JCT		² GPR at Station (mV/A)		² GPR at Junction (mV/A)	
Bonding Wires	Ring Gap on Cable Shield	¹ Measured	Modelled	¹ Measured	Modelled
Isolated	Closed	88.40/ <u>16</u> (2.83 kV)	71.90/ <u>17</u> (2.30 kV)	146.04/ <u>47</u> (4.67 kV)	137.97/ <u>35</u> (4.42 kV)
Isolated	Opened	4.25/ <u>99</u> (136 V)	N/A	333.82/ <u>12</u> (10.68 kV)	318.57/ <u>12</u> (10.19 kV)
Connected	Closed	92.30/ <u>19</u> (2.95 kV)	75.35/ <u>18</u> (2.41 kV)	133.69/ <u>37</u> (4.28 kV)	127.05/ <u>35</u> (4.07 kV)
Connected	Opened	-	74.18/ <u>18</u> (2.37 kV)	-	130.41/ <u>35</u> (4.17 kV)

1. Computed from measurements.
2. In brackets: GPR for an ultimate HV ground fault current of 32 kA.

TABLE 5

MARKHAM MTS #2 - CURRENT SPLITS (A)
(With Current Injection Between Station Ground and Remote Ground)

<u>Current Path</u>	<u>Test Condition 1</u>		<u>Test condition 2</u>		<u>Test Condition 6</u>		<u>Test Condition 7</u>	
	<u>Measured</u>	<u>Modelled</u>	<u>Measured</u>	<u>Modelled</u>	<u>Measured</u>	<u>Modelled</u>	<u>Measured</u>	<u>Modelled</u>
Cable Shield	0.572/ <u>20</u>	0.682/ <u>15</u>	N/A	N/A	0.818/ <u>14</u>	-	N/A	N/A
Bond Wires	N/A	N/A	N/A	N/A	0.253/ <u>178</u>	-	0.530/ <u>17</u>	0.638/ <u>13</u>
Total	N/A	N/A	N/A	N/A	0.580/ <u>21</u>	0.672/ <u>14</u>	N/A	N/A
Skywires	0.482/ <u>20</u>	0.627/ <u>13</u>	0.069/ <u>43</u>	0.114/ <u>41</u>	0.487/ <u>22</u>	0.619/ <u>13</u>	-	0.590/ <u>11</u>
Distr. Neutrals	0.396/ <u>-35</u>	0.317/ <u>-42</u>	0.825/ <u>-10</u>	0.820/ <u>-14</u>	0.405/ <u>-31</u>	0.317/ <u>-40</u>	-	0.329/ <u>-34</u>
Station Ground	0.143/ <u>12</u>	0.110/ <u>16</u>	0.236/ <u>37</u>	0.285/ <u>44</u>	0.111/ <u>0</u>	0.109/ <u>20</u>	-	0.115/ <u>24</u>
Junction ground	0.088/ <u>20</u>	0.062/ <u>39</u>	0.069/ <u>43</u>	0.114/ <u>40</u>	0.093/ <u>16</u>	0.060/ <u>37</u>	-	0.051/ <u>29</u>

See Table 1 for test conditions.

TABLE 6

MARKHAM MTS #2 - CURRENT SPLITS (A)
(With Current Injection Between Station and Junction Grounds)

<u>Current Path</u>	<u>Test Condition 3</u>		<u>Test Condition 4</u>		<u>Test Condition 5</u>	
	<u>Measured</u>	<u>Modelled</u>	<u>Measured</u>	<u>Modelled</u>	<u>Measured</u>	<u>Modelled</u>
Cable Shield	N/A	N/A	0.981/ <u>-1</u>	0.985/ <u>1</u>	0.971/ <u>6</u>	-
Bond Wires	N/A	N/A	N/A	N/A	0.094/ <u>-66</u>	-
Total	N/A	N/A	N/A	N/A	1.003/ <u>1</u>	0.998/ <u>1</u>
Skywires	-	0.768/ <u>-8</u>	0.006/ <u>-22</u>	0.017/ <u>-43</u>	0.003/ <u>171</u>	0.003/ <u>-53</u>
Distr. Neutrals	0.812/ <u>-10</u>	0.820/ <u>-14</u>	-	0.018/ <u>-55</u>	-	0.003/ <u>-59</u>
Station Ground	0.245/ <u>35</u>	0.285/ <u>44</u>	-	0.006/ <u>12</u>	-	0.001/ <u>-1</u>
Junction Ground	-	0.259/ <u>24</u>	0.022/ <u>52</u>	0.006/ <u>-15</u>	0.0004/ <u>0</u>	0.001/ <u>-21</u>

See Table 1 for test conditions.

TABLE 7

MARKHAM MTS #2 - TOTAL EXPOSURE ON OPEN CONDUCTORS (mV/A)

<u>Open Conductor</u>	<u>Test Condition 1</u>		<u>Test Condition 2</u>		<u>Test Condition 3</u>	
	<u>Measured</u>	<u>Modelled</u>	<u>Measured</u>	<u>Modelled</u>	<u>Measured</u>	<u>Modelled</u>
Test Circuit Bond Wire	22.9/ <u>-108</u>	22.7/ <u>-109</u>	453.2/ <u>50</u>	528.4/ <u>52</u>	804.4/ <u>33</u>	797.3/ <u>36</u>
Adj. Circuit Bond Wire	53.1/ <u>-115</u>	42.2/ <u>-112</u>	403.1/ <u>45</u>	489.7/ <u>48</u>	764.4/ <u>30</u>	768.4/ <u>33</u>
Test Circuit R- ϕ Shield	26.4/ <u>-109</u>	25.3/ <u>-110</u>	444.4/ <u>49</u>	522.8/ <u>51</u>	-	793.1/ <u>36</u>
Test Circuit W- ϕ Shield	18.8/ <u>-105</u>	20.1/ <u>-108</u>	-	533.6/ <u>52</u>	808.8/ <u>35</u>	801.3/ <u>37</u>
Test Circuit B- ϕ Shield	N /A	N/A	502.2/ <u>55</u>	598.6/ <u>55</u>	826.6/ <u>38</u>	856.4/ <u>40</u>

See Table 1 for test conditions.

TABLE 8

MARKHAM MTS #2 - MESH VOLTAGES (mV/A)

(With Current Injection Between Station Ground and Remote Ground)

<u>Test Condition</u> <u>(See Table 1)</u>	<u>Mesh Voltage at Station</u>		<u>Mesh Voltage at Junction</u>	
	<u>Measured</u>	<u>Modelled</u>	<u>Measured</u>	<u>Modelled</u>
1	2.58/ <u>16</u>	13.27/ <u>16</u>	-	11.89/ <u>39</u>
2	-	34.30/ <u>44</u>	-	21.73/ <u>40</u>
6	6.73/ <u>18</u>	13.09/ <u>20</u>	-	11.45/ <u>37</u>
7	-	13.77/ <u>24</u>	-	9.80/ <u>29</u>

TABLE 9

MARKHAM MTS #2 - STEP VOLTAGES (mV/A)
(With Current Injection Between Station Ground and Remote Ground)

Test Condition (See Table 1)	Step Voltage at Station		Step Voltage at Junction	
	<u>Measured</u>	<u>Modelled</u>	<u>Measured</u>	<u>Modelled</u>
1	-	7.03/16	-	12.52/39
2	0.52/37	18.17/44	-	22.87/40
6	3.60/20	6.94/20	5.09/38	12.06/37
7	-	7.30/24	-	10.31/29

TABLE 10

MARKHAM MTS #2 - FENCE TOUCH VOLTAGES (mV/A)
(With Current Injection Between Station ground and Remote Ground)

Test Condition	Touching Fence From	Touch Voltage at Station		Touch Voltage at Junction	
		<u>Measured</u>	<u>Modelled</u>	<u>Measured</u>	<u>Modelled</u>
1	Outside	0.71/12	5.64/16	3.09/40	7.19/39
	Inside	8.38/15	-	14.51/38	-
2	Outside	0.33/40	14.57/44	10.13/35	13.13/40
	Inside	18.75/31	-	23.24/31	-
6	Outside	0.16/12	5.56/20	16.71/37	6.92/37
	Inside	7.42/20	-	10.22/37	-
7	Outside	-	5.85/24	-	5.92/29
	Inside	-	-	-	-

4.0 MODELLED RESULTS

Appendix A summarizes the formulas used in the calculations, other than those given in the references.

4.1 Soil Resistivity

A uniform soil resistivity of 113 $\Omega \cdot m$ was derived as an average of the measured apparent soil resistivities from survey #1, neglecting the lower measured values to be conservative. A two-layer interpretation of the measured results from survey #2 using the method given in Appendix D of the Grounding Guide /1/, yielded a top layer of 35 $\Omega \cdot m$, thickness 1.6 m and a bottom layer of 140 $\Omega \cdot m$ and resulted in an equivalent uniform soil resistivity of 84 $\Omega \cdot m$ for an estimated station radius of 40 m. Based on the average of the two results, an equivalent soil resistivity of 100 $\Omega \cdot m$ was used in calculating the grounding system performance at the station and at the junction.

4.2 Isolated Ground Resistances

An isolated station ground resistance R_{gs} of 0.69 Ω was calculated using equation 3.1 of the Grounding Guide /1/, based on an estimated station radius of 40 m and 1550 m of buried grid conductors at the station. Similarly, an isolated ground resistance R_{gj} of 2.1 Ω was calculated for the junction based on an estimated radius of 13 m and 510 m of buried grid conductors at the junction.

4.3 Fault Current Shielding Factors

For a HV ground fault, the fault current entering the station is reduced by a shielding factor S_1 (conductive component) due to the bonding conductors and/or the cable shield which may be bonded to the station ground through the ring gap, with the grounded conductors carrying the remaining current back to the source (inductive component). The shielding factors were calculated based on mutual couplings between the faulted phase (test circuit) and the ground return conductors. The conductor spacings are indicated in Figure 3. The calculated shielding factors are 0.237/-6 due to the two bonding conductors alone and 0.094/-81 due to the cable shield alone (see Appendix of /2/ for calculation procedure). A net shielding factor of 0.018/-88 due to the bonding conductors and the cable shield was calculated based on cascading of their individual shielding factors. The inductive component of the fault current returning through the grounded conductors is calculated as $(1-S_1) I_f$, where I_f is the total fault current.

At the junction, the shielding factor S_1 changes to that of the overhead line. For the skywires of the 230-kV circuits, a shielding factor S_2 of 0.588/-12 was calculated from the skywire self and mutual impedances. This requires an additional source of $(S_2 - S_1) I_f$ at the junction.

4.4 Conductive Equivalent Circuit

Figures 4 and 5 show the conductive equivalent circuits for a HV fault at the station and at the junction with respect to fault current sources and current distribution.

For the two 159 mm² (19 AWG) Alumoweld skywires of the 230-kV double circuit line, the conductor earth return self and mutual impedances were calculated as 0.749/64 Ω/km and 0.331/80 Ω/km respectively, using Carson's simplified formulas. Based on an estimated tower footing resistance of 2.5 Ω and a span length of 263 m, the conductive skywire chain impedance Z_{sk} was calculated as 0.702/32 Ω .

For the two 253 mm² (500 kcmil), RWU-90, XLPE insulated, copper bonding conductors between the station and junction grids, the combined conductive earth return impedance was calculated as 0.648/81 Ω /km (0.168/81 Ω for 260 m length), using Carson's simplified formulas. The HV cable shields are bonded to the junction grid and are connected to the station grid through ring gaps. In the event of a ground fault, the ring gap on the faulted circuit may operate, thereby bonding the HV cable shield to the station grid. For each HV cable shield, the conductive impedance was calculated as 0.764/80 Ω /km (0.20/80 Ω for 260 m length) using the procedure explained in /2/. With the 500 kcmil conductors and the cable shield bonded to the station grid, an equivalent conductive impedance Z_c of 0.154/82 Ω was calculated based on an equivalent GMR of 0.383 m for all three conductors.

For the eight 28-kV distribution feeders, a net neutral impedance Z_n of 0.24/58 Ω was estimated based on the geometry shown in Figure 1. For the 507 mm² (1000 kcmil) copper, XLPE, concentric neutral feeder cables and the 127 mm² (250 kcmil) copper neutral conductors which are installed in underground ducts inside the station, an equivalent GMR of 0.2 m was assumed for each duct. For the feeders carried on poles outside the station with 85 mm² (3/0 AWG) ACSR ground conductors, distribution taps were assumed at 200 m spacings with first tap at 500 m from the station and service taps at 100 m spacings with a ground resistance of 10 Ω due to water pipe connections.

4.5 Tolerable Limits of Touch and Step Voltages

The tolerable touch and step voltages were calculated as 575 V and 1857 V respectively, assuming a surface layer of 80 mm of crushed stone using equations 2.4 and 2.2 of the Grounding Guide /1/.

4.6 Modelled Results for a HV Fault at the Station

The equivalent circuit in Figure 4 was solved for a fault current of 1.00/0 A and the calculated current splits are given in Table 5, along with the measured results. Note that the current splits in the cable shield, bonding conductors and the skywires are the sum of the conductive and inductive components.

The ground potential rises at the station and at the junction were calculated as the product of the ground current split and the isolated ground resistance. Table 3 compares the modelled ground potential rises with the measured results. The ground potential rises for an ultimate HV ground fault current of 32 kA are also given in the tables in brackets.

Voltages between the station ground and the isolated grounding conductors installed between the station and the junction were calculated as the sum of the longitudinal induced voltage and the difference in the ground potential rises at the station and at the junction. The calculated results are compared with the measured results in Table 7. The induced voltages were calculated based on mutual couplings between the conductors using Sunde's formulas for mutual impedance of finite length earth return conductors /3/. The mutual coupling between the shield and its enclosed phase conductor was calculated using the procedure explained in the Appendix of /2/.

The mesh and step voltages were calculated using equation 3.6 of the Grounding Guide /1/ and equation 73 of the IEEE Guide 80 /4/, respectively. The touch voltage outside the fence was calculated using equation 3.11 of the Grounding Guide /1/. Here, a distance of 1 m between the fence and the grid, and a spacing of 10 m between parallel grid conductors were assumed at the station. At the junction, a distance of 3 m between the fence and the grid, and a spacing of 4 m between parallel grid conductors were assumed. The estimated touch and step voltages at the station and the junction are given in Tables 8, 9 and 10, along with measured results.

4.7 Modelled Results for a HV Fault at the Junction

The grounding system performance in the event of a HV ground fault at the junction was estimated with and without bonding between the station and junction grids. The conductive circuit impedances, shielding factors and the formulas used in their calculations are as explained in the previous sections. Here, the equivalent circuit in Figure 5 was solved for a fault current of 1.00/0 A and the resulting ground current splits are given in Table 11.

TABLE 11

MARKHAM MTS #2 - MODELLED CURRENT SPLITS (A)
(With Current Injection Between Junction Ground and Remote Ground)

<u>Grounding Connection Between TS and JCT</u>		<u>Current Split in Station Ground</u>	<u>Current Split in Junction Ground</u>
<u>Bonding Wires</u>	<u>Ring Gap on Shield</u>		
Isolated	Closed	0.104/17	0.066/35
Isolated	Opened	NIL	0.152/12
Connected	Closed	0.109/18	0.061/35
Connected	Opened	0.108/18	0.062/35

The calculated ground potential rises are presented in Table 4 along with measured results. Note that the two ground grids would be conductively isolated with the cable shield and the bonding conductors both isolated at the station and therefore, no significant current would return through the station ground to cause GPR at the station.

The modelled mesh, fence touch and step voltages are given in Table 12. The calculated results with the two ground grids bonded through either the cable shield or the bonding conductors alone vary only marginally from the values with bonding through both of them and therefore, only the latter results are presented in Table 12.

TABLE 12

MARKHAM MTS #2 - MODELLED TOUCH AND STEP VOLTAGES (mV/A)
(With Current Injection Between Junction Ground and Remote Ground)

<u>Parameter</u>	<u>¹With Ground Grids Bonded</u>		<u>With Ground Grids Isolated</u>	
	<u>At Station</u>	<u>At Junction</u>	<u>At Station</u>	<u>At Junction</u>
Mesh Voltage	13.13/18	11.53/35	N/A	28.91/12
Step Voltage	6.96/18	12.14/35	N/A	30.44/12
Fence Outside Touch Voltage	5.58/18	6.97/35	N/A	17.47/12

1. Bonded through the cable shield and bonding conductors.

5.0 DISCUSSION OF RESULTS

- a) The differences in the measured apparent soil resistivities from the Wenner surveys (see 2) may be due to local variations in the soil conditions and overly deep probe insertion for short spacings. The results show a reasonably uniform resistivity of 100 Ω .m.
- b) For a HV ground fault at the station with the cable shield bonded to the station grid (ring gap operating), the measured and modelled station ground potential rises for an ultimate fault current of 32 kA are both well below the allowable limit of 5 kV, but approach the recommended limit of 3 kV. The 253 mm² (500 kcmil) bonding conductors joining the two grids did not have a significant effect in further reducing the GPR due to the effective shielding of the HV cable. However, the station GPR would exceed the allowable limit of 5 kV without the bonding conductors if the ring gap did not operate (cable shield opened). In this event, the bonding conductors are necessary to limit the station GPR to below the recommended value of 3 kV.
- c) The junction GPR for the above station fault current of 32 kA is generally kept under the permissible limit of 5 kV with bonding between the two grids through the cable shield and/or the bonding conductors. The higher GPR at the junction than at the station is probably due to the high ground resistance and change in shielding at the junction. Simplified calculations indicated that a significant further reduction (approximately 20% - 25%) could be obtained by bonding the tower bases of the adjacent 500-kV and 230-kV circuits. This would also improve the GPR at the station (by approximately 20%) which otherwise approaches the recommended limit of 3 kV. In this case, a 500-kV fault should not result in a worst case GPR at the station or at the junction. A detailed study was not considered necessary at this time.
- d) The currents entering the station and junction grounds were found to be less than 15% and 10% of the fault current respectively, for a HV station fault with the two ground grids interconnected (see Table 5). These reduced ground current splits are mainly due to the shielding of the HV circuit. The LV distribution system with its feeder neutrals tied to the station grid also has significant influence in reducing the ground current splits. Approximately 57% of the current returned through the cable shield, as measured with the bonding conductors isolated, due to the change in the shielding of the HV cable to that of the skywire. The bonding conductors in parallel with the cable shield between the two grids did not significantly reduce the ground current split due to induction from the shield current. However with the cable shield isolated, the bonding conductors carried approximately 53% of the fault current. The distribution neutrals carried approximately 40% of the fault current with the two ground grids interconnected and approximately 82% of the fault current with the grids isolated (see Table 5).
- e) In the event of a HV fault at the junction with the two ground grids bonded through the cable shield and/or the bonding conductors, the station ground potential rises for a fault current of 32 kA would be under the recommended limit of 3 kV, but the junction GPR would exceed the limit approaching the allowable limit of 5 kV. With the two grids isolated, the GPR at the junction for the above fault current of 32 kA would considerably exceed the permissible limit of 5 kV due to the large ground current split. Here, the entire fault current splits between the skywires and the junction ground with the skywires carrying approximately 85% of the fault current and the remaining 15% entering the junction ground, as modelled. A HV fault at the junction with isolated ground grids will not cause significant GPR at the station and measurements confirmed this.

- f) The isolated station ground resistance derived from the measured GPR and current splits varied between 0.65 Ω and 0.86 Ω and compares reasonably with the calculated value of 0.69 Ω . The junction ground resistance derived from the measurements varied between 1.45 Ω and 2.75 Ω , compared to the calculated value of 2.1 Ω . The ground resistances estimated from current split measurements are typically not very accurate in view of the relatively small ground current components. Also the isolated ground resistances are of little importance compared to the other parameters such as shielding effectiveness of the HV circuits and LV distribution neutrals in reducing the ground potential rise.
- g) The measured and modelled mesh voltages at the station and at the junction for a HV fault current of 32 kA with the two ground grids interconnected through the cable shield and/or the bonding conductors are all within the tolerable touch voltage limit of 575 V. The measured and modelled step voltages are all under the tolerable limit of 1857 V. Compared to the measured mesh and step voltages, the model should be conservative.
- h) The relatively high voltages (approximately 16% to 30% of the GPR) measured between the fence and the ground grid as well as the considerably lower measured fence touch voltages compared to the GPR indicate that the fences at the station and at the junction are both isolated from their respective ground grids as shown in the station drawings. For an ultimate HV fault current of 32 kA with the two ground grids interconnected through the cable shield and/or the bonding conductors, the measured and modelled fence touch voltages are all within the tolerable touch voltage limit of 575 V. The measured results are lower than the modelled values, probably due to the gradient control conductors installed along the fences.
- i) Calculations indicated that the mesh and fence touch voltages at the station and junction for the above fault current of 32 kA with the two ground grids isolated would exceed the tolerable touch voltage limit due to the large ground current splits.
- j) The measured total exposure given in Table 7 should be useful in future selection of surge arresters to replace the ring gaps at the station. The measured and modelled exposure values agree reasonably.

6.0 CONCLUSIONS

- a) An equivalent soil resistivity of 100 $\Omega \cdot m$ was derived from the Wenner test data for calculating the grounding system performance at the station and at the junction.
- b) The isolated ground resistances calculated from the grid geometries are 0.69 Ω at the station and 2.1 Ω at the junction and are consistent with the tested results.
- c) For a HV ground fault at the station or at the junction with the cable shield of the faulted circuit bonded to the station ground grid (ring gap operating), the ground potential rise at the station for an ultimate fault current of 32 kA would be well under the allowable limit of 5 kV, but approaching the recommended limit of 3 kV. The ground potential rise at the junction for the above fault current of 32 kA would exceed or approach the permissible limit of 5 kV.
- d) With the cable shield of the faulted circuit bonded to the station grid (ring gap operating), the 253 mm² (500 kcmil) bonding conductors joining the two ground grids did not significantly reduce the station and junction ground potential rises, due to the effective shielding of the HV cable.

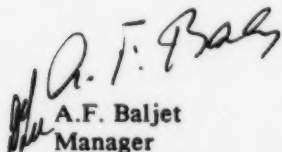
- e) In the event of a HV ground fault at the station or at the junction with the cable shield of the faulted circuit open (ring gap not operating), the two ground grids would be conductively isolated without the bonding conductors and the ground potential rises at the station and junction for the above fault current of 32 kA would increase considerably beyond the permissible limit of 5 kV. In this event, the bonding conductors are necessary to limit the ground potential rises below the recommended value of 3 kV.
- f) The ground potential rise at the junction is higher than that at the station mainly due to the high ground resistance and change in shielding at the junction. The junction GPR for a HV fault current of 32 kA generally approaches or exceeds the permissible limit of 5 kV.
- g) Simplified calculations indicate that a significant reduction (approximately 20% - 25%) in the junction GPR could be obtained by bonding the adjacent 500-kV and 230-kV tower bases at the junction. This should also improve the station GPR (by approximately 20%) which otherwise approaches the recommended limit.
- h) For a HV station or junction fault with the two ground grids interconnected through the cable shield and/or the bonding conductors, the currents entering the station and junction grounds were found to be less than 15% and 10% of the fault current respectively. These reduced ground current splits are mainly due to good shielding of the HV circuit and the interconnected LV distribution neutrals. At the junction, approximately 48% of the fault current returned through the skywires (both inductive and conductive components) and the distribution neutrals carried approximately 40% of the fault current, as measured. A current split of 53% to 58% was measured on the cable shield and/or the bonding conductors at the station.
- i) The mesh and fence touch voltages at the station and at the junction for an ultimate HV station fault current of 32 kA with the two ground grids interconnected through the cable shield and/or the bonding conductors are all within the tolerable touch voltage limit of 575 V, but would exceed the limit for isolated grids as modelled.
- j) Measurements confirmed that the station and junction fences are isolated from their respective ground grids as indicated in the station drawings.
- k) The step voltages at the station and at the junction for the above HV fault current of 32 kA are all under the tolerable step voltage limit of 1857 V.
- l) The measured total exposure (see Table 7) should be useful in future selection of surge arresters to replace ring gaps at the station.
- m) Simplified models were developed to validate the measurements and should be useful for checking the effect of future changes and estimating grounding system performances at other similar stations. The models were chosen to require only the use of a hand calculator.

7.0 ACKNOWLEDGMENTS

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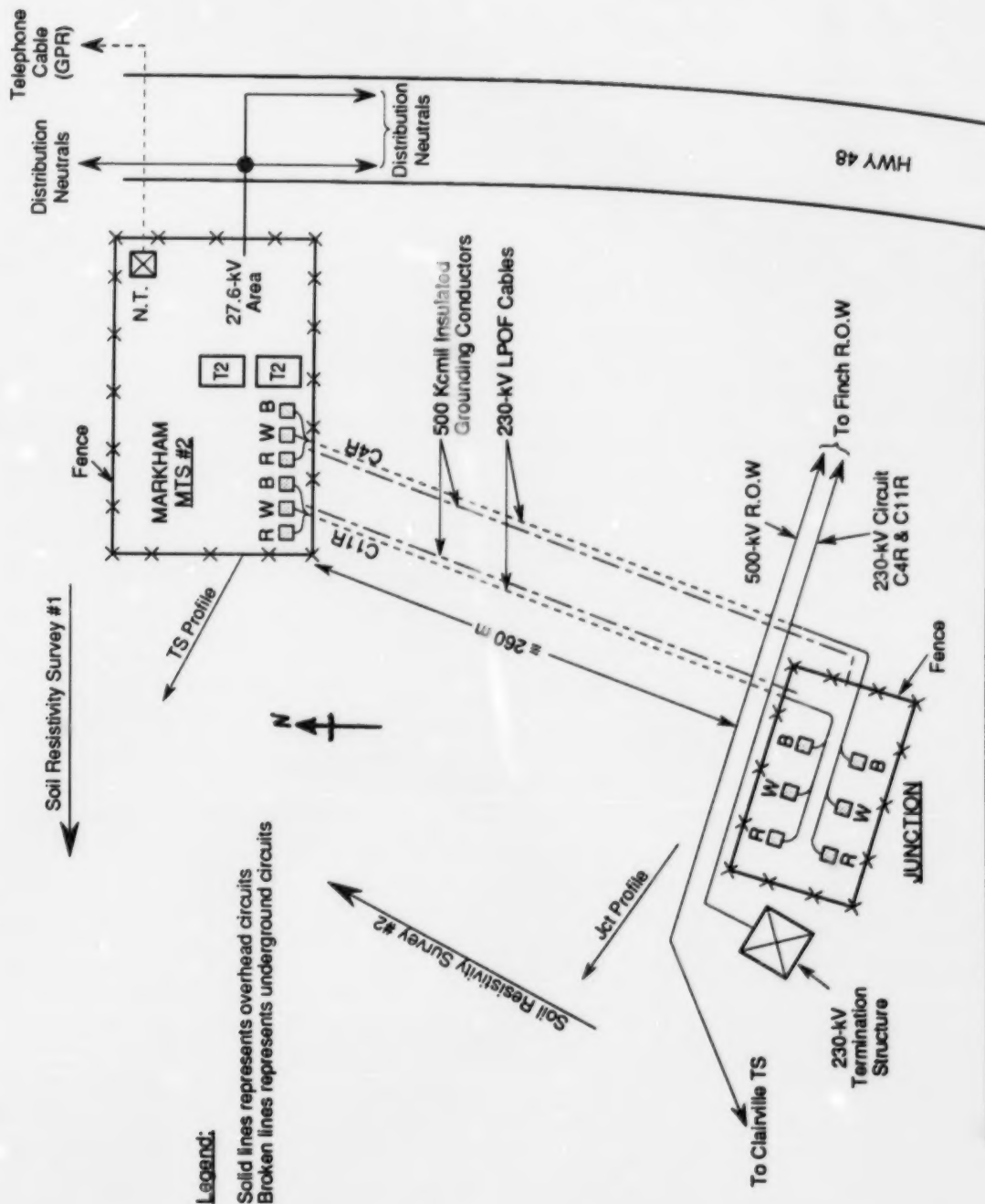


FIGURE 1

LAYOUT OF MARKHAM MTS #2 AND LINE/CABLE JUNCTION WITH RESPECT TO GROUNDING TESTS

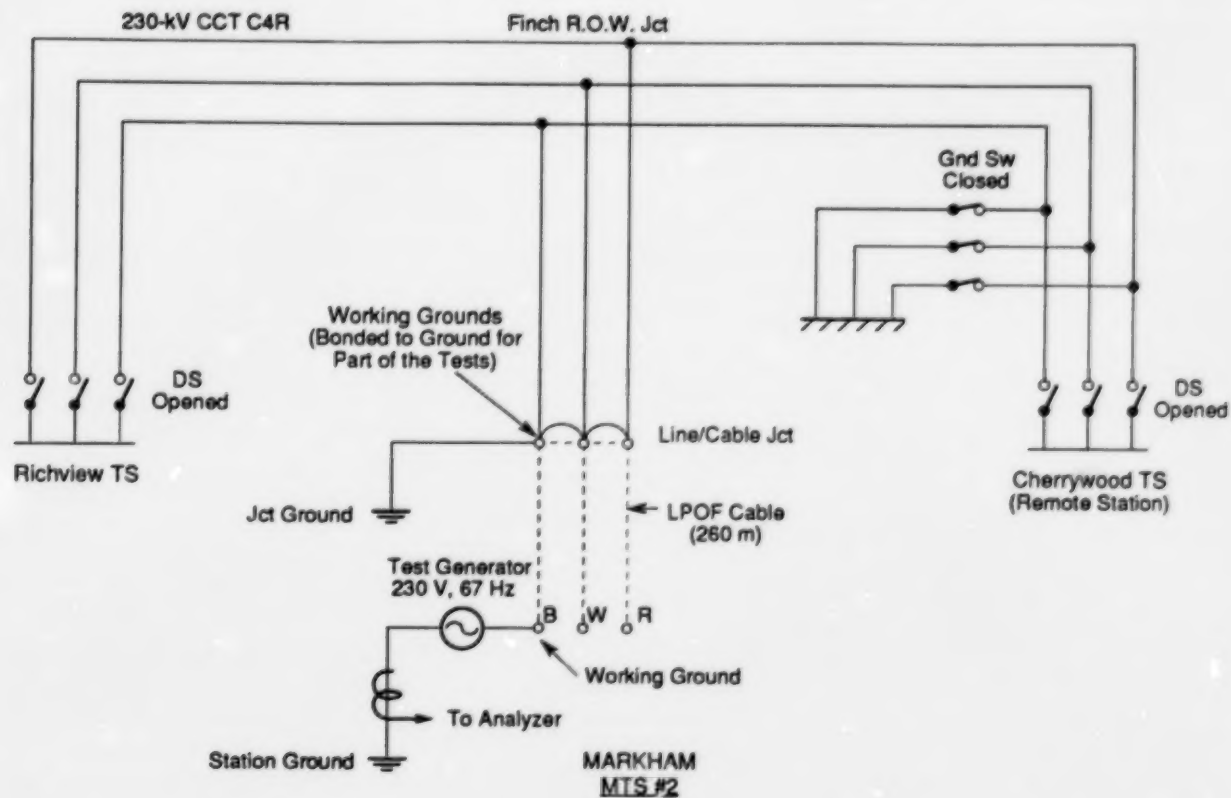
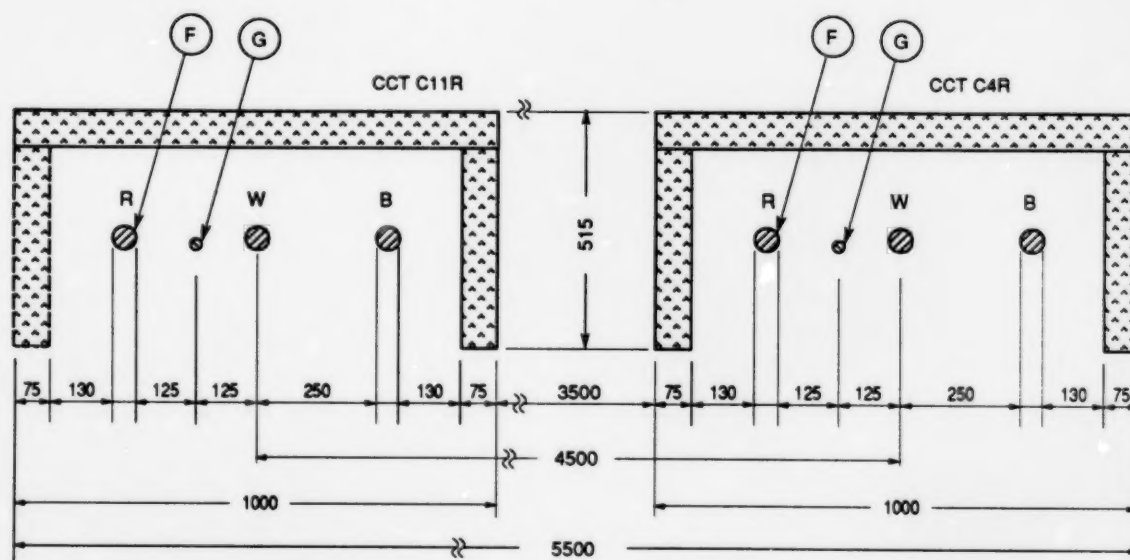


FIGURE 2
MARKHAM MTS #2 GROUNDING TESTS
CURRENT INJECTION CIRCUIT

- (F) 230-kV LPOF Cable
- (G) 500 kCMIL Copper Conductor



All Dimensions in mm.

FIGURE 3
MARKHAM MTS #2
SPACING OF CONDUCTORS BETWEEN JUNCTION AND STATION

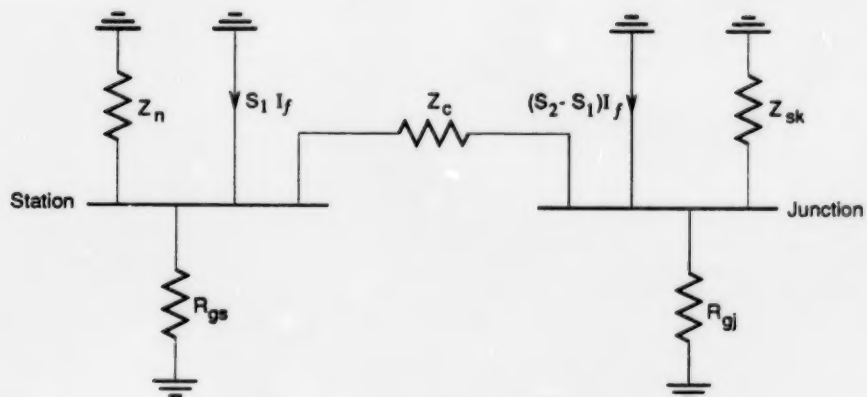


FIGURE 4
MARKHAM MTS #2
CONDUCTIVE EQUIVALENT CIRCUIT FOR A
HV FAULT AT THE STATION

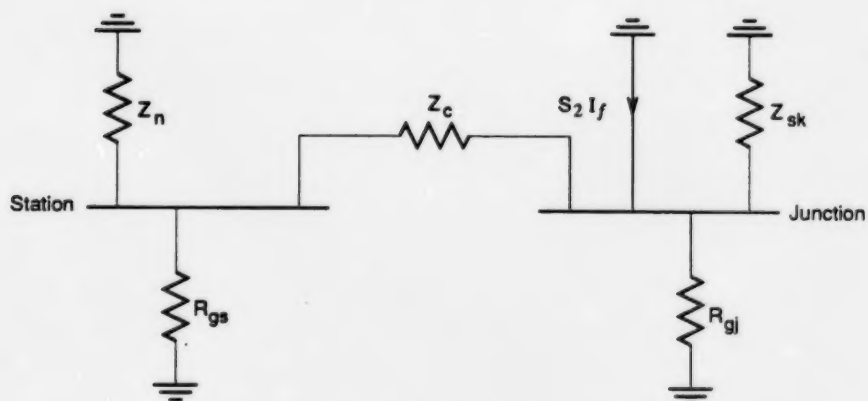


FIGURE 5
MARKHAM MTS #2
CONDUCTIVE EQUIVALENT CIRCUIT FOR A
HV FAULT AT THE JUNCTION

APPENDIX A

SUMMARY OF FORMULAS USED IN GROUNDING CALCULATIONS

1. Conductor Earth Return Self Impedance, Z_s

$$Z_s = R_s + jX_s \quad (\Omega/\text{km}) \quad (1)$$

$$R_s = 0.059 + R_{ac} \quad (\Omega/\text{km}) \quad (2)$$

$$X_s = 0.0377 \ln (8440 \rho_s / \text{GMR}^2) \quad (3)$$

Where, R_{ac} = conductor ac resistance (Ω/km)

ρ_s = soil resistivity ($\Omega\cdot\text{m}$)

GMR = conductor geometric mean radius (m)

For pipes or shields, R_{ac} and X_{ac} (conductor internal reactance added to X_s) are calculated as shown in Ontario Hydro Research report No. 83-433-K, dated November 7, 1983, by E.P. Dick.

2. Conductor Earth Return Mutual Impedance, Z_m

$$Z_m = R_m + jX_m \quad (\Omega/\text{km}) \quad (4)$$

$$R_m = 0.0377 \tan^{-1} (8440 \rho_s / \text{GMD}^2) \quad (5)$$

$$X_m = 0.0377 \ln [(8440 \rho_s / \text{GMD}^2) + 1] \quad (\Omega/\text{km}) \quad (6)$$

Where, ρ_s = soil resistivity ($\Omega\cdot\text{m}$)

GMD = geometric mean distance between conductors (m)

3. Tower Footing Resistance, R_t

For four Augured Footing

$$R_t = 0.25 (R_s + R_{m1} + R_{m2} + R_{m3}) \quad (9)$$

Where, R_s = footing self resistance from equation (8)

R_{m1}, R_{m2}, R_{m3} = mutual resistances to other footings
from equation (10)

$$R_m = [\rho_s / (2 \pi L)] [\ln \{ (L/x) + \text{SQRT}(1+(L^2/x^2)) \}] \quad (\Omega) \quad (10)$$

Where, L = footing length (m)

x = distance to the other footings in turn (m)

4. Chain Impedance of Skywires, Z_c

$$Z_c = Z_s + l R_t \quad (\Omega) \quad (11)$$

Where, Z_s = conductor earth return self impedance (Ω/km)

l = span length (km)

R_t = tower footing resistance (Ω)

5. Shielding Factor, S

$$S = 1 - (Z_m / Z_s) \quad (12)$$

Where, Z_m = conductor earth return mutual impedance (Ω/km)

Z_s = conductor earth return self impedance (Ω/km)